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Explosion/Blast Dynamics for Constellation Launch Vehicles Assessment

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1.0 Authorization and Notification

The NASA Engineering and Safety Center (NESC) was requested to support the Explosion/Blast Dynamics for Constellation Launch Vehicles Assessment Review. This assessment was approved out-of-board on June 4, 2007 by Mr. Ralph Roe, NESC Director. This assessment was led by Mr. Mel Baer, Sandia National Laboratories (SNL) Senior Scientist, and co-led by Mr. Clint Cragg, NESC Principal Engineer. The Assessment Plan was approved by the NESC Review Board (NRB) on January 30, 2008. The key stakeholders for this assessment methodology are Ray Silvestri and Leo Langston of Johnson Space Center (JSC).

The NESC team was tasked to perform an independent review of data and provide consultation on the following:

1. The team was asked to provide recommendations for quantitative characterization of a potential blast environment resulting from an inadvertent release of liquid fuel and oxidant based on the current Ares-1 configuration and feasible failure causes (both supplied by NASA).
2. The team was also asked to describe best practices procedures to enable characterization of most likely explosion environments of the Ares-1 Crew Launch Vehicle.

2.0 Signature Page

Team signature page on file 5/29/08

Mr. Mel Baer, Team Lead	Date	Mr. Charles Hickox	Date
Mr. Arthur Ratzel	Date	Mr. David Crawford	Date
Mr. Marlin Kipp	Date	Mr. Gene Hertel	Date
Mr. Hal Morgan	Date		

3.0 List of Team Members

Name	Position/TDT Affiliation	Center/Contractor
Core Team		
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Dave Crawford	Shock Physics Code Development	Sandia National Laboratories
Charles Hickox	Fluid Flow Analysis	Sandia National Laboratories
Marlin Kipp	Shock Physics Analysis	Sandia National Laboratories
Gene Hertel	General Technical Manager	Sandia National Laboratories
Hal Morgan	Program Manager	Sandia National Laboratories
Arthur Ratzel	Director, Engineering Sciences	Sandia National Laboratories
Leo Langston	Stakeholder	JSC
Ray Silvestri	Stakeholder	JSC
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Charles Schafer	NESC Chief Engineer	MSFC
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Laura Leybold	MTSO Program Analyst	LaRC
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4.0 Executive Summary

An assessment methodology is developed to guide quantitative predictions of adverse physical environments and the subsequent effects on the Ares-1 crew launch vehicle associated with the loss of containment of cryogenic liquid propellants from the upper stage during ascent. Development of the methodology is led by a team at SNL with guidance and support from a number of NASA personnel. The methodology is based on the current Ares-1 design and feasible accident scenarios. These scenarios address containment failure from debris impact or structural response to pressure or blast loading from an external source. Once containment is breached, the envisioned assessment methodology includes predictions for the sequence of physical processes stemming from cryogenic tank failure. The investigative techniques, analysis paths, and numerical simulations that comprise the proposed methodology are summarized and appropriate simulation software is identified.

5.0 Assessment Plan

The assessment methodology was developed by a team from SNL with guidance and support from personnel at Langley Research Center (LaRC), Johnson Space Center (JSC), and Marshall Space Flight Center (MSFC). Participants in the assessment are listed in the team table in Section 3.0. It should be emphasized that a general assessment methodology was developed and is not based on particular accident scenarios. It is anticipated that future analyses of specific accidents will follow the approach established by this methodology.

This assessment methodology was based on:

1. Review of NASA documents which describe the Ares-1 Crew Launch Vehicle (CLV);
2. Review of prior experimental programs which consider the potential for explosions resulting from the mixing of liquid oxygen (LO2) and liquid hydrogen (LH2);
3. Identification of generic accident scenarios to provide a focus for the development;
4. Identification of the possible sequence of events corresponding to generic accident scenarios;
5. Identification of the types of analyses required to predict the environments and resulting effects of hypothesized accidents;
6. Identification of computational software suitable for the required simulations; and
7. Requirements for the validation of predictions. It was not possible to develop a highly specific assessment methodology because precise accident scenarios details were not specified.

To compensate for this lack of information, generic accident scenarios were identified which exhibit possible adverse effects on the Ares-1 CLV. It is believed that these scenarios cover a range of possible failure mechanisms and sequences of events that could produce explosion hazards.

6.0 Description of the Problem and Proposed Solutions

6.1 Description of Problem

An assessment methodology is established for the quantitative prediction of physical environments and subsequent vehicle interactions associated with a potential blast environment resulting from an inadvertent release of liquid fuel and oxidant from the US of the Ares-1 CLV during ascent. This work is pursued under an agreement between SNL and the NESC. The methodology is based on the current Ares-1 configuration and proposed feasible accident scenarios [ref 1]. Feasible accident scenarios are to be defined by NASA. Hence, the development of an assessment methodology must be based on assumed, generic accident scenarios. The methodology described herein is intended to increase confidence in the assumptions, methods, and analyses that could be conducted to make key technical recommendations and decisions affecting vehicle design, crew survival, and ascent abort procedures relating to the survival from a blast environment. This includes defining best practice procedures for the characterization of explosion environments.

For purposes of Launch Abort System (LAS) design for the Ares-1 system, there is a need to understand and characterize the potential explosion environment produced by a release of liquid propellant from the US. It is important to understand the environments associated with such a catastrophic failure in terms of the blast, debris, and thermal characteristics at the Crew Module (CM) during separation from the failing vehicle as part of the Launch Abort Vehicle. Both near-field and far-field initial blast properties must be considered. Key features of appropriate methodologies include defining the key physics that need to be modeled, determining appropriate inputs to these models, identifying appropriate modeling tools for simulation and defining the expected model outputs for characterizing the blast and transport of material and energy in relation to the interaction with the CM (or other parts of the vehicle).

In discussing the potentially explosive environment, the terms explosion, detonation, and deflagration will be used and brief definitions of these terms are given in Section 12. More detailed definitions of these terms can be found in the book [ref. 2], by Kuo (1977). The focus of any methodology for the prediction of a propellant explosion necessarily centers on the release of hydrogen from the storage tank in the US and the subsequent mixing and reaction with oxygen causing rapid energy release. An initial analysis methodology was outlined and summarized in a PowerPoint presentation dated January 24, 2008. The associated slides are reproduced in Appendix A. This presentation forms the basis for the subsequent discussion of the developed methodology.

6.2 Overview of Methodology

As stated above, the methodology to be described is based on the inadvertent release of propellants and the possible consequences associated with such a release. A meaningful prediction of a potential explosion event requires fundamentally that the entire sequence of processes associated with cryogenic tank rupture, venting, and mixing of the hydrogen with oxygen or ambient air be described in detail. A series of four steps is envisioned as a path to determining the consequences of a loss of containment of propellants that can occur either externally or internally to the stage structure:

1. Define the accident scenarios (NASA responsibility);
2. Determine the initial conditions for a potential blast environment;
3. Predict the pressure, impulse, thermal, and debris sources; and
4. Determine the environment at the crew exploration vehicle (CEV).

Each of these steps is described in the subsequent sections. Following identification of the fundamental steps, a summary of the general types of simulation software required for the proposed predictions is discussed and specific existing computational software packages are identified that are potentially suitable for the required simulations.

6.2.1 Accident Scenarios

Credible accidents that could result in the loss of containment of propellants include:

1. Debris from a solid rocket booster explosion breaching an exterior propellant tank wall;
2. Debris lost from structures forward of the stage breaching an exterior propellant tank wall;
3. Energy release sufficient to cause catastrophic rupture of propellant tanks; and
4. Pressure imbalance between hydrogen and oxygen tanks leading to failure of the common bulkhead which separates the propellants.

Since a specific accident scenario has not been identified, the proposed methodology is illustrated with reference to a sequence of events. Once specific accident scenarios have been identified, it is necessary to identify both the relevant physical processes to be addressed and specific computational software that can be used to provide useful simulations.

6.2.2 Initial Conditions for the Blast Environment

Initial conditions leading to a potential blast environment are derived from the details of the accident scenarios, and include, but are not limited to:

1. Location on the US tanks where breach of the cryogenic tanks occurs;
2. Modes of failure of the tank(s) (*e*.g. holes, cracks or tears of material associated with rupture of the tanks)
3. Availability of oxygen (*e.g*., ambient atmosphere and/or subsequent failure of liquid oxidant tank);
4. Tank pressures and temperatures of the hydrogen, oxygen and/or ambient air determining the thermodynamic states associated with the mixing and stoichiometry of a potential combustion event;
5. Confinement or the degree of intimate contact of the hydrogen-oxygen mixture determining whether a deflagration can evolve into a detonation; and
6. Trajectory data including available fuel volume, relative vehicle velocity and ambient air free-field conditions.

6.2.3 Pressure, Impulse, Thermal, and Debris Source Terms

The pressure, impulse, thermal and debris environments, at selected altitudes, can be estimated upon specifying the above initial conditions. The existing White Sands Test Facility (WSTF) experimental data [ref. 3] (Bunker-Farrah, R, et al., 2002) provides much insight into propellant explosion behavior and measurements from these tests can provide guidance in estimating the combustion/energy release rates. However, to supplement this historical database, additional hydrogen/oxygen experiments may be needed to reflect conditions that are more relevant to expected accident conditions, *i.e.* rupture of a single compartment of the tank configuration that potentially causes subsequent failure of the auxiliary tank; failure of a common bulkhead; and/or dynamic environment effects.

The essential ingredients of a potential explosion require that hydrogen and oxygen be brought together as either gases or liquids. Since these constituents are originally separated and stored as liquids, the turbulent mixing of these reactants must be modeled. Subsequently, the ignition of the mixture must then be considered. Based on prior work from WSTF, self ignition is likely to occur (without any external source) when the liquids first come in contact. Under conditions of weak confinement, the initial mixing and combustion behavior produces rapid gas formation and energy release that likely drives the propellants apart and impedes (rather than enhances) gross mixing of the non-premixed reactants. Typically, these reactive processes of liquid propellants produce rapid deflagrations rather than detonations and the blast waves from these explosions are characterized by much lower source pressures and impulse than otherwise realized by high explosives of equivalent energy release. Hence, it is important to use an appropriate model for turbulent combustion with timescales that partition the energy release supporting blast *vs.* waste heat (volumetric combustion behavior) and reflects limited combustion behavior. For example, a volumetric energy source can be used in shock physics analysis to represent the turbulent combustion environment that induce blast effects due to distributed energy release [ref 4] (Ritzel, D.V. and Matthews, K., 1997). The fireball characteristics can be estimated using traditional existing correlations to determine the thermal environment [ref 5] (Baker, et al., 1983). The rate of energy release during the reaction determines the pressure and the impulse at the CEV, as well as the characteristics of the ejected debris (*i.e.* a non-shock event should produce relatively large fragments moving at relatively low velocities).

6.2.4 Environment at the CEV

The environment at the CEV is determined from analyses that define near- and far-field effects. The nature of the explosion event covers a broad range of time scales and the various aspects of relevant physics are weakly coupled. Hence, structural failure of the tanks, venting, mixing of the reactants, combustion, blast and structural response of the CEV can be modeled sequentially, using the output from one event as initial conditions for the next. A fully coupled fluid/structural analysis is likely not required and one-way coupling should be adequate in these assessments. The near-field effects include blast over-pressure/impulse, heat transfer and debris environment at the CEV while still attached to the US. The consequences of debris dispersal are determined by mass/velocity characteristics of the debris ejected from the US that intersects the CEV. The far-field effects include defining blast over-pressure/impulse, heat transfer, and debris environments at the CEV. In addition, the thermal and debris insults to the parachutes during an abort should be considered. Launch abort timing relative to an explosion is critical in order to determine the CEV environment.

6.2.5 Simulation Software

A broad spectrum of numerical analysis tools is required to perform the analyses described. A suggested list of computational codes is included in Table 6.2-1, where all software packages are available at SNL and an asterisk indicates SNL-developed software. It is anticipated that both commercially available and laboratory-developed software (SNL or elsewhere) will be required to perform the suite of simulations required to meet the requirements of the developed methodology in a timely manner.

Table 6.2-1. Summary of Computational Analysis Codes

Code	Analysis Capabilities
FLOW3D; FLUENT	Computational fluid dynamics / turbulent flow / mixing / reaction
CHEETAH	Define high pressure product EOS and thermo-chemistry
CTH*	Shock physics, blast environment, debris formation
PRESTO*; JAS3D*; ABAQUS	Structural mechanics
CALORE*, COYOTE*	Thermal analysis
PREMO*	Aerodynamics

Computational fluid dynamics (CFD) (*e.g.* FLOW3D, FLUENT) codes are required to assess the mixing and reaction of the released hydrogen with on-board oxygen and/or ambient air. The cryogenic fluids, hydrogen and oxygen, must change to mixed vapor phases in order to promptly react and this transformation likely occurs as a dense mixture. A chemical equilibrium code (*e.g.* CHEETAH) with non-ideal gas capability is needed to define the equation of state, thermo-chemistry, and energy release capabilities of the potentially dense state reactant mixture. The actual energy release is required in shock physics analysis codes (*e.g.* CTH) to determine blast environment (ullage pressure and impulse histories) and thermal field of the fireball. The consequent debris characterization and impact dynamics can also be estimated with the shock physics code. Structural, thermal, and aerodynamics codes (*e.g.* PRESTO, CALORE, PREMO, respectively) are also required to fully address the response to the blast environment.

The required fidelity of simulations (*i.e.*, level of detail in the models and physics required to assure that all the significant factors/geometry are included) must be determined. This investigation should include benchmark models and/or analyses of example past accidents.

There is a wealth of hydrogen explosion experimental data available; however, not all of it may be relevant to a tank failure scenario. To gain some additional insight, the WSTF LH2/LO2 data could be reanalyzed whereby a distributed energy release is modeled rather than treated as a point explosive source (*i.e.*, volume explosion *vs.* high explosive (HE) detonation). Additional experiments could be conducted to gain an understanding of this blast environment whereby different breakup conditions of the propellant tanks are postulated that are more representative of actual mixing conditions.

In addition to the expertise at SNL, consultation with outside expertise is likely to prove fruitful. For example, Professor J. E. Shepherd (Caltech) is an internationally recognized expert in hydrogen explosion/ blast characterization and has assisted SNL in several other prior studies of volumetric explosion behavior.

6.2.6 Summary

The sequence of tasks to determine the consequences of propellant release (internal and/or external to the stage structure) is summarized as follows:

1. Define/assess the potential credible accidents that would release propellants and cause a subsequent explosion;
2. Evaluate/interpret existing experimental data;
3. Determine the initial conditions for propellant release and/or mixing derived from details of the accident scenarios;
4. Identify the wide spectrum of computational tools required for the analyses;
5. Determine the energy release and possible blast effects for the scenario(s) of interest;
6. Use the blast environment to define both the near- and far-field pressure/impulse/debris effects; and
7. Assess potential accident consequences on the CEV.

6.3 Accident Scenario Considerations

In section 6.2.1 a set of possible accident scenarios is listed; however, details and data needed for failure assessment (*i.e.* debris propagation from the explosion of the First Stage solid propellant to the US) are not currently available. Hence, an alternate approach is to assume that the Second Stage propellant tanks are breached and omit consideration of the details of accidents that may adversely affect the tanks. Regardless of the scenario definition, the path of events leading to a potential explosion in the US, centers on breach of the propellant tanks and on the modes of failure that dictate how venting and mixing of the propellants subsequently occur.

One proposed accident scenario is an "explosion" of the First Stage solid rocket motor which would create a source of debris that might impact the exterior of the US LH2 and/or LO2 fuel tank walls. The credibility of this scenario depends on whether a debris trajectory intersects the US. The First Stage has a slightly smaller diameter than the US, and ejected debris does not have an unimpeded path to the exterior walls of the US. If at the time of the accident, the First Stage has rotated off the system axis relative to the US, a path intersection possibly exists. Under normal aligned conditions, analyses could determine if there are adequate aerodynamic forces on upward moving debris in a relatively downward-moving airstream that would change the trajectory of debris towards the US. In particular, there may be some mechanism whereby reacting propellant fragments might be accelerated into the upper tank walls. In any case, fragments would have velocity components aligned with the longitudinal direction of the tanks, and would likely gash or crack the tank walls rather than puncture them. This failure mode could occur in either the liquid or ullage region of a tank. Since the propellant tanks are pressurized, a sudden loss in ullage pressure in one tank could lead to structural failure of the adjacent propellant tank *via* the common bulkhead. Another possible outcome of a loss of pressure is a boiling liquid expanding vapor explosion, or BLEVE, [ref. 5] (Baker, et al., 1983). In such an event, the sudden drop in pressure inside a propellant tank causes violent boiling of the liquid propellant that liberates large amounts of vapor to potentially cause a secondary explosion.

If the solid rocket motor propellant detonates, the motor case and propellant fragments are expected to be ejected at velocities >1 km/s. Debris dimensions in the vicinity of the detonation can be estimated with a fragmentation model [ref. 6], (*e.g*., Grady-Kipp, 1989). This method is more applicable in events where the energy is sufficiently high to produce many fragments than under other situations where only a few fragments form, such as tearing conditions. If the solid rocket motor case bursts under elevated internal pressure, the debris will be dispersed with much lower velocities than those of a detonation and the physical size of the debris fragments would be expected to be much greater than those produced by a detonation.

In either a detonation or lower energetic “explosion” event, there will be shock waves transmitted to the US that could potentially cause an imbalance of pressure in the propellant tanks, and possible failure of the common bulkhead. This scenario would require a fairly detailed model of the intervening structure and components coupling the shock from the explosion to the US. Clearly, the details of the accident scenario have a major influence in determining the propagation path of failure mechanisms leading to the onset of a potential explosion of the liquid propellants.

7.0 Proposed Analyses

The following discussion describes analyses proposed to gain insight into accident scenarios in which either or both US tank(s) is/are perforated by debris fragment(s) originating from the First Stage or experience structural failure(s) caused by blast loading. The source of fragments and subsequent impacts are not considered in this discussion. The accident could occur at any time during the First Stage burn, so the US tanks are assumed to be fully loaded, with nominal ullage volumes and pressures. The oxygen tank is located aft of the hydrogen tank and separation of the tanks is maintained by a common bulkhead. There are five tank wall perforation scenarios, as illustrated in Figure 7.0-1, for which analysis paths should be pursued:

1. Perforation of the oxygen tank in the fluid region;
2. Perforation of the oxygen tank in the ullage region;
3. Perforation of the hydrogen tank in the fluid region;
4. Perforation of the hydrogen tank in the ullage region, and
5. Structural response to blast loading. Each of these scenarios is considered in turn.

Following the discussion of the individual scenarios, some brief considerations are considered that relate to the debris source and debris interaction with the propellant tanks.

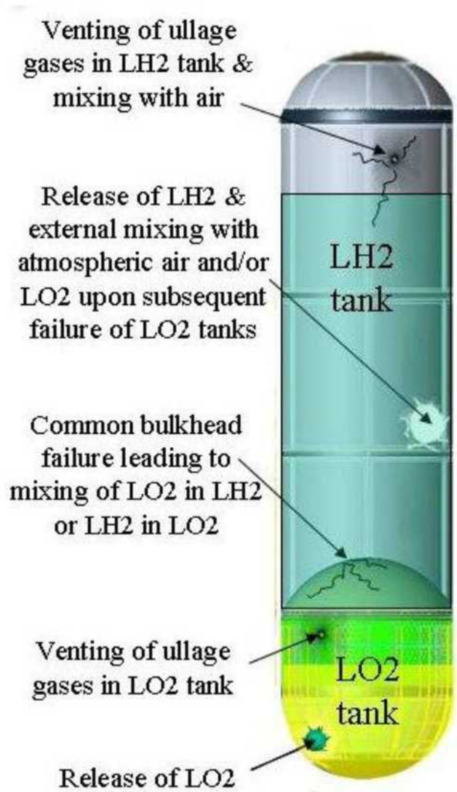

Figure 7.0-1. Possible Failure Locations in the US Propellant Tanks

7.1 Perforation of the Oxygen Tank in the Liquid Region

Perforation of the exterior oxygen tank wall in the fluid region could result in loss of liquid at a rate that depends on the internal fluid pressure and the size of the penetration opening(s). Structural analysis of the region surrounding these openings is necessary to determine whether there is sufficient pressure difference to enhance venting due to additional structural failure (*e.g.* tearing). The flow of liquid oxygen into the airstream is not expected to lead immediately to an explosion since there is no fuel present. However, the loss of oxygen will increase the ullage volume, and if the ullage pressure cannot be maintained, rapid boiling of the oxygen could produce an imbalance of pressure across the common bulkhead. Structural analyses, complementing design modeling, are required to determine the consequences of this imbalance, and whether failure of the common bulkhead occurs. If the common bulkhead fails, a flow of hydrogen aft into the oxygen tank can occur, accompanied by boiling of the hydrogen and intense turbulent mixing. This would potentially lead to formation of a highly reactive mixture. If auto-ignition occurs, rapid combustion and energy release will likely lead to complete tank wall failure. The time to failure depends on the initial size of the vent area and ullage pressure.

7.2 Perforation of the Oxygen Tank in the Ullage Region

Perforation of the exterior tank wall in the ullage region of the oxygen tank will result in venting of the ullage gas (helium and oxygen) into the airstream. If venting causes a rapid pressure loss, the oxygen could boil in this region and also vent the ullage gases. As in Section 7.1, the vented oxygen in the absence of hydrogen does not pose an explosion hazard, however, the resulting pressure imbalance across the common bulkhead must be analyzed to determine whether it fails and how much oxygen remains prior to the failure. Upon common bulkhead failure, the mixing of hydrogen with the remaining oxygen could form a combustible mixture.

7.3 Perforation of the Hydrogen Tank in the Fluid Region

Perforation of the exterior tank wall in the region of the liquid hydrogen fuel could result in flow of the hydrogen into the airstream, and rapid vaporization. A hydrogen-air mixture is combustible; however, the plume of vapor is likely to be fuel rich and would require an ignition source rather than being auto-catalytic. Hence, it is unclear when burning occurs and where the reacting plume(s) impinge on the aft structures. Failure of the ullage pressure would also result in boiling of the hydrogen into the ullage region that could cause a pressure imbalance across the common bulkhead. For this condition, the ullage gas in the oxygen tank is at higher pressure than the hydrogen, and it is assumed that ullage and oxygen will be forced into the liquid hydrogen should that failure of the common bulkhead occurs. The higher temperature of the oxygen causes the hydrogen to boil with intense turbulent mixing to form a combustible mixture.

7.4 Perforation of the Hydrogen Tank in the Ullage Region

Perforation of the exterior tank wall in the ullage region of the hydrogen tank could result in the venting of ullage gas into the airstream. If the vent rate is high, the loss in pressure could result in hydrogen boiling, and venting of the ullage gases. Ignition of this mixture could be possible, with potential of thermal damage to the exterior of the US, and possibly to the First Stage. If a pressure imbalance should occur, the scenario becomes similar to that of Section 7.3.

7.5 Structural Response to Blast Loading

Pressure impulse loading of the propellant tanks can possibly induce a structural response that results in failure of the internal common bulkhead or an external breach of either or both tanks. The consequences of an internal common bulkhead failure are discussed in Section 7.1 and the consequences of external breaches are considered in Sections 7.1-4. Detailed structural analyses are required to predict the responses to pressure loadings

7.6 Comments on Debris Interaction with Tanks and Energy Release

In the scenario where the source of debris is from the First Stage, the angle at which the fragment must engage the US exterior wall is necessarily shallow, and damage area is more likely to be a gash rather than a simple clean entry that a projectile would inflict. Perforation is expected to lead eventually to rupture of the external tank wall and/or the common bulkhead, but this failure depends on pressure loss rates. Knowledge of design load thresholds for the common bulkhead is particularly important for consequences analyses if pressure imbalance develops across the common bulkhead.

For a specified insult to a tank wall, a combination of fluid and structural code analyses are required to follow the sequence of flow and structural responses that determine the strength of the energy release of the hydrogen/oxygen mixture formed. If the mixture reaction is primarily a deflagration, then thermal analyses are required to ascertain the damage to the structure as well as the environment at the CEV. If the rate of formation and/or confinement leads to a reaction that transforms with sufficiently rapid energy release to create pressure and/or shock waves, then a shock code (*e.g.*, CTH) must be employed to track the effects of the blast on the CEV. If timing of the event is such that the module is already in an escape mode, the thermal and pressure loads as a function of radial extent must be determined to assess consequences to the vehicle.

7.7 Recommended Methodology/Integrated Analyses

The NESC team describes the integrated analyses paths which constitute a recommended methodology for the assessment of generic accident scenarios. The overall methodology is depicted in the flowcharts given below in Figures 7.7-1 through 7.7-4 which serve to guide the subsequent discussion of the methodology. Consider Figure 7.7-1 which depicts the initial steps of the proposed analyses. It is necessary to define a suite of credible accident scenarios which affect the US and specify the initial conditions to be imposed on the US. For purposes of developing the methodology presented here, we have identified conceptual scenarios that address a foreseeable range of accident environments to which the US may be subjected. The general types of accidents are summarized in Section 6.2.1 and include:

- Debris from a solid rocket booster explosion penetrating one or both of the liquid propellant tanks.
- Debris lost from structures forward of the US penetrating one or both of the liquid propellant tanks.
- Blast, pressure, or impulse loading sufficient to cause breaching or catastrophic rupture of one or both liquid propellant tanks.
- Blast, pressure, or impulse loading sufficient to cause internal barrier failure between the liquid propellant tanks.

The initial conditions applicable to the US must be determined for each of the general conceptual accident types. The specific accident scenarios that can result are identified in Section 7.0 as:

1. Perforation of the oxygen tank in the fluid region;
2. Perforation of the of the oxygen tank in the ullage region;
3. Perforation of the hydrogen tank in the fluid region;
4. Perforation of the hydrogen tank in the ullage region; and
5. Tank failure resulting from structural response to a blast or pressure loading.

Prior to the analysis of specific scenarios, it is desirable to validate the simulation strategy to the extent possible against available experiments that address the mixing and subsequent reactions involving LO2 and LH2. This activity is noted in Figure 7.7-1 as a supporting analysis linked to the main flowchart with a dashed line.

There are three main paths of analysis identified in Figure 7.7-1 which depend on whether penetration of the LO2 tank or LH2 tank occurs or whether failure is the result of a structural failure cause by pressure, impulse, or blast loading. In the following we summarize the steps in the analyses required to characterize the responses associated with each of the scenarios.

Scenarios 1 and 2: Perforation of the LO2 tank in the fluid or ullage regions requires the analysis process depicted in Figure 7.7-2. The external venting process must be simulated to determine if oxygen merely vents to the exterior region or if the venting process induces additional structural response. If only venting to the exterior occurs, it may be assumed there are no adverse effects since there is no contact with the hydrogen confined in the LH2 tank. If it is determined that the venting process induces a structural response, then a structural analysis is required to determine if there is a subsequent structural failure that results in contact between the oxygen and hydrogen, *e.g.* a failure of the internal common bulkhead which separates LO2 and LH2, or a failure of containment which results in contact of LO2 and LH2 external to the US. When there is a structural failure that results in contact between the propellants, the mixing and phase change processes must be modeled. Simultaneous with the mixing process, it is necessary to simulate the combustion behavior to determine the ultimate response associated with the contact of the propellants or the possible contact of LH2 with atmospheric air. These simulations must span the possibilities from confined internal mixing to mixing external to the US or a combination of the two. Ultimately, the simulations can require considerations of dynamic structural response, transient turbulent, two-phase incompressible and compressible CFD, and reactive chemistry. The end result of the simulation process is a prediction of pressure, impulse, blast, and thermal environments produced by the envisioned accident scenario. Computational software available for the required simulations (and those discussed subsequently) is listed in Table 6.2-1.

Scenarios 3 and 4: Perforation of the LH2 tank in the fluid or ullage regions requires the analysis process depicted in Figure 7.7-3. The analysis procedure and required simulations are the same as those discussed in regard to Scenarios 1 and 2, except in one aspect. The only difference is that for Scenarios 3 and 4 external mixing of hydrogen with atmospheric air must be considered when only an external venting occurs. The analysis path for external venting requires the same steps encountered for any of the mixing processes identified. When external mixing occurs, aerodynamic effects can be important which require additional considerations regarding CFD simulation.

Scenario 5: Structural failure caused by pressure, impulse, or blast loading requires the analysis process depicted in Figure 7.7-4. In this scenario, detailed structural simulations are required to predict likely failure modes. The propellants can be brought into contact externally or internally, depending on the mode of structural failure. Mixing and reactive processes can thus occur between the propellants external or internal to the US. In addition, external mixing and reaction may occur between LH2 and atmospheric oxygen.

Comment on External Mixing: Although not specifically included as a separate scenario in Scenarios 1-4, it is possible that LO2 and LH2 tanks are breached externally at essentially the same time thus leading to the need to consider mixing of the propellants external to the US. This type mixing has been included as part of Scenario 5. In any proposed scenario, it is reasonable to determine if there is a possibility for contact of the propellants external to the US. A high degree of dilution is anticipated for any leakage of propellants into the external environment and results from the high relative velocity between the US and the atmosphere and the rapid phase changes associated with propellant tank blow-down. It seems likely that a simulation, based on a worst case external mixing scenario, could determine if there is any likelihood of an adverse environment resulting from external mixing. If it is determined that no adverse environment can be produced, it may not be necessary to include simulations of external mixing in any of the other scenarios.

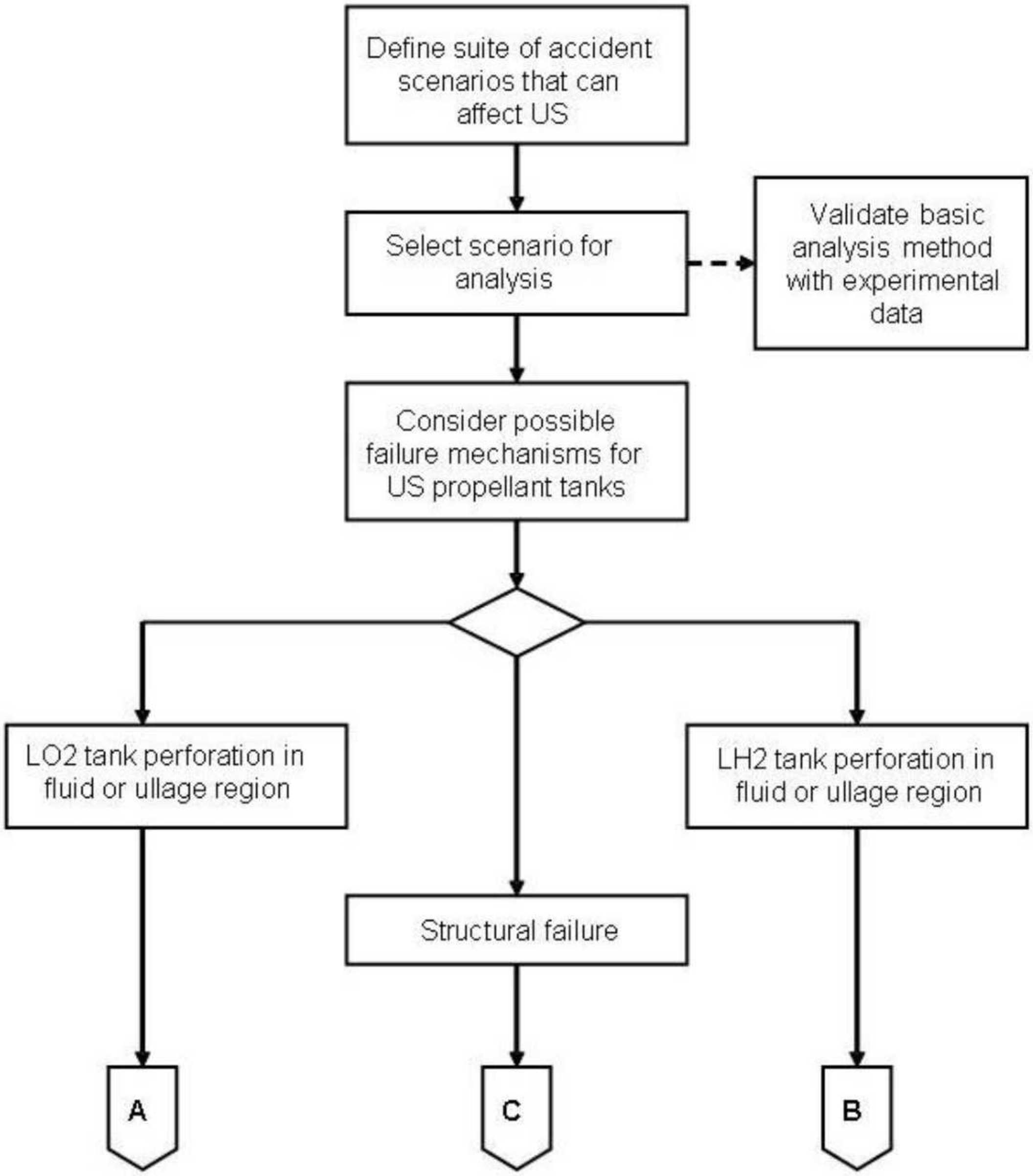

Figure 7.7-1. Initial Analysis Path

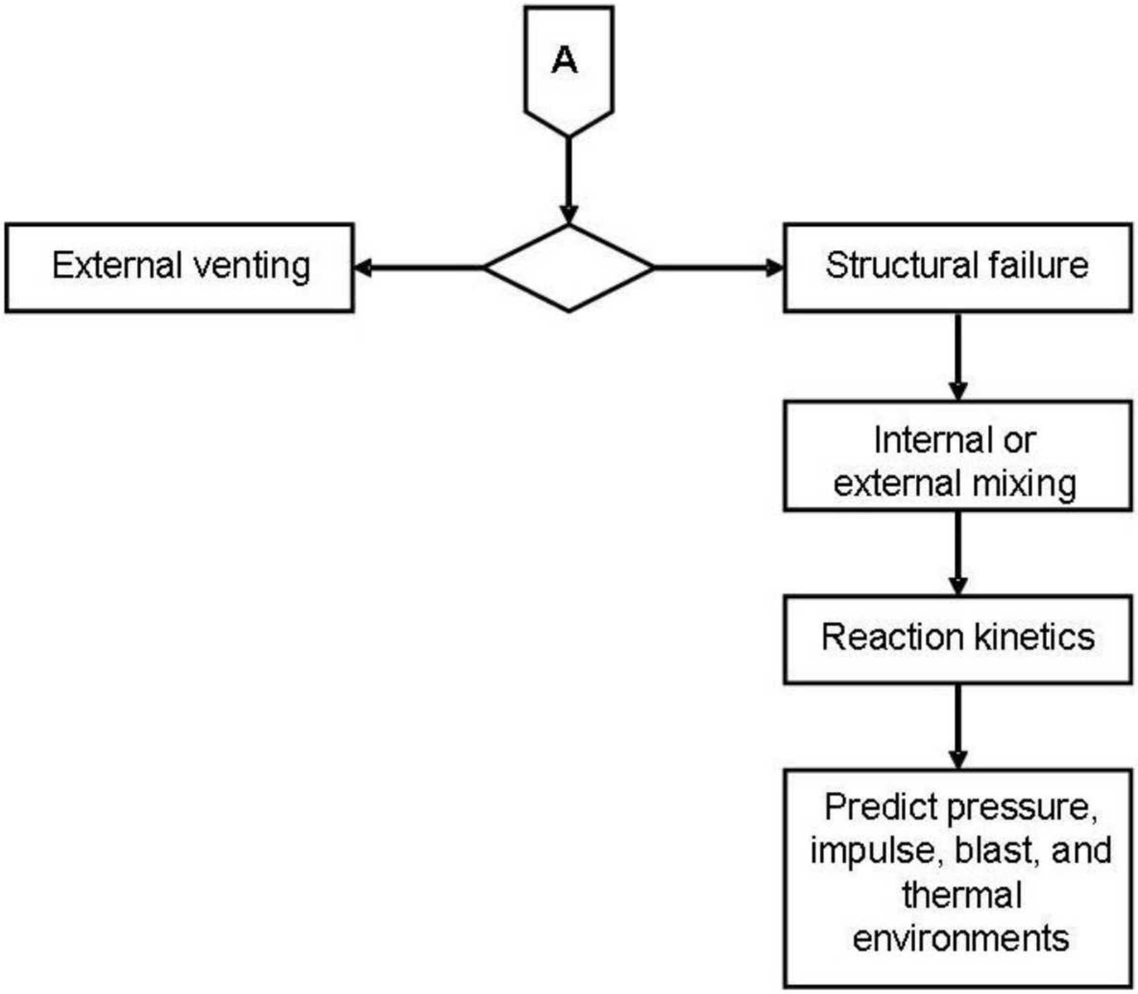

Figure 7.7-2. Analysis Path for LO2 Tank Failure

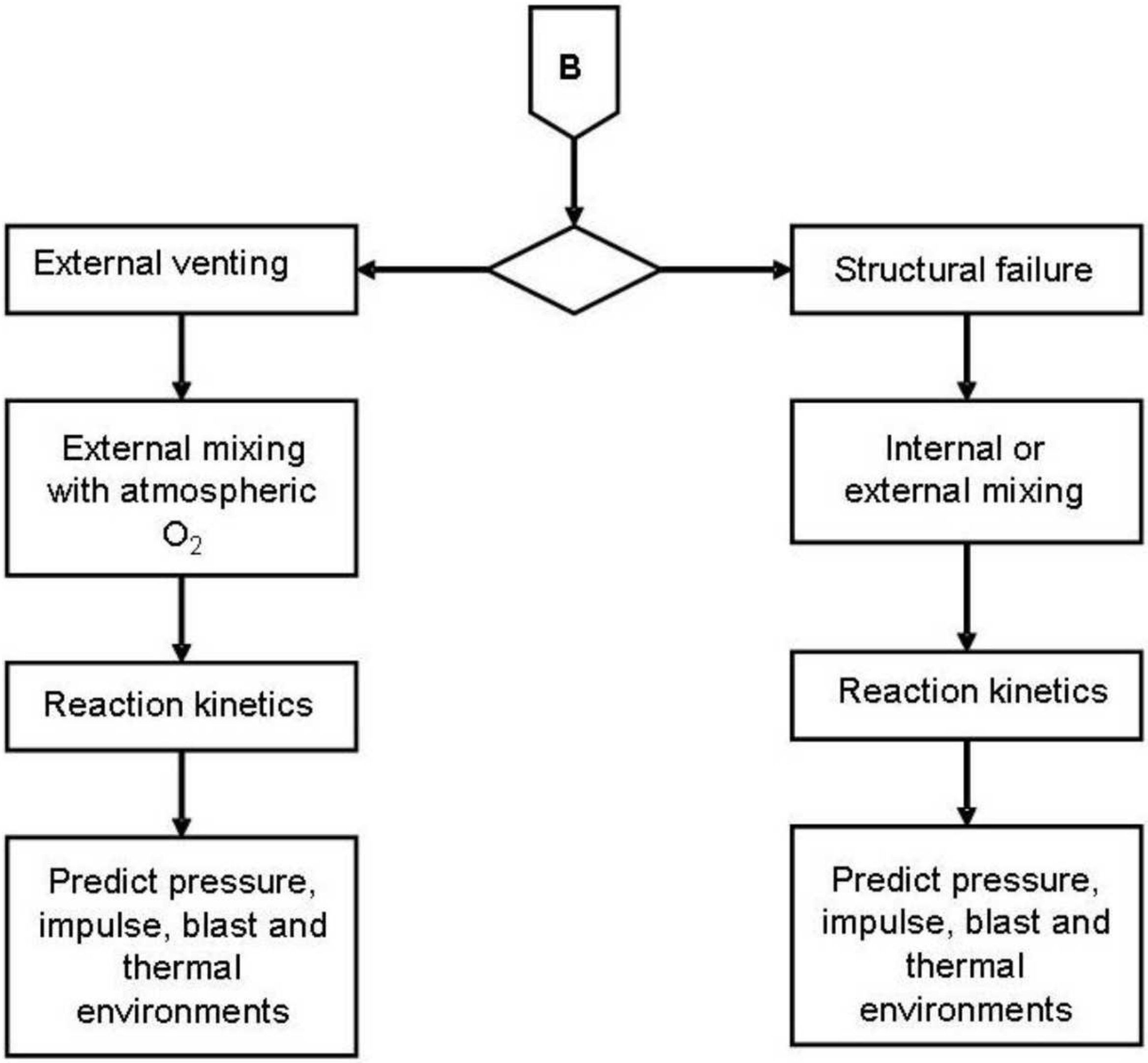

Figure 7.7-3. Analysis Path for LH2 Tank Failure

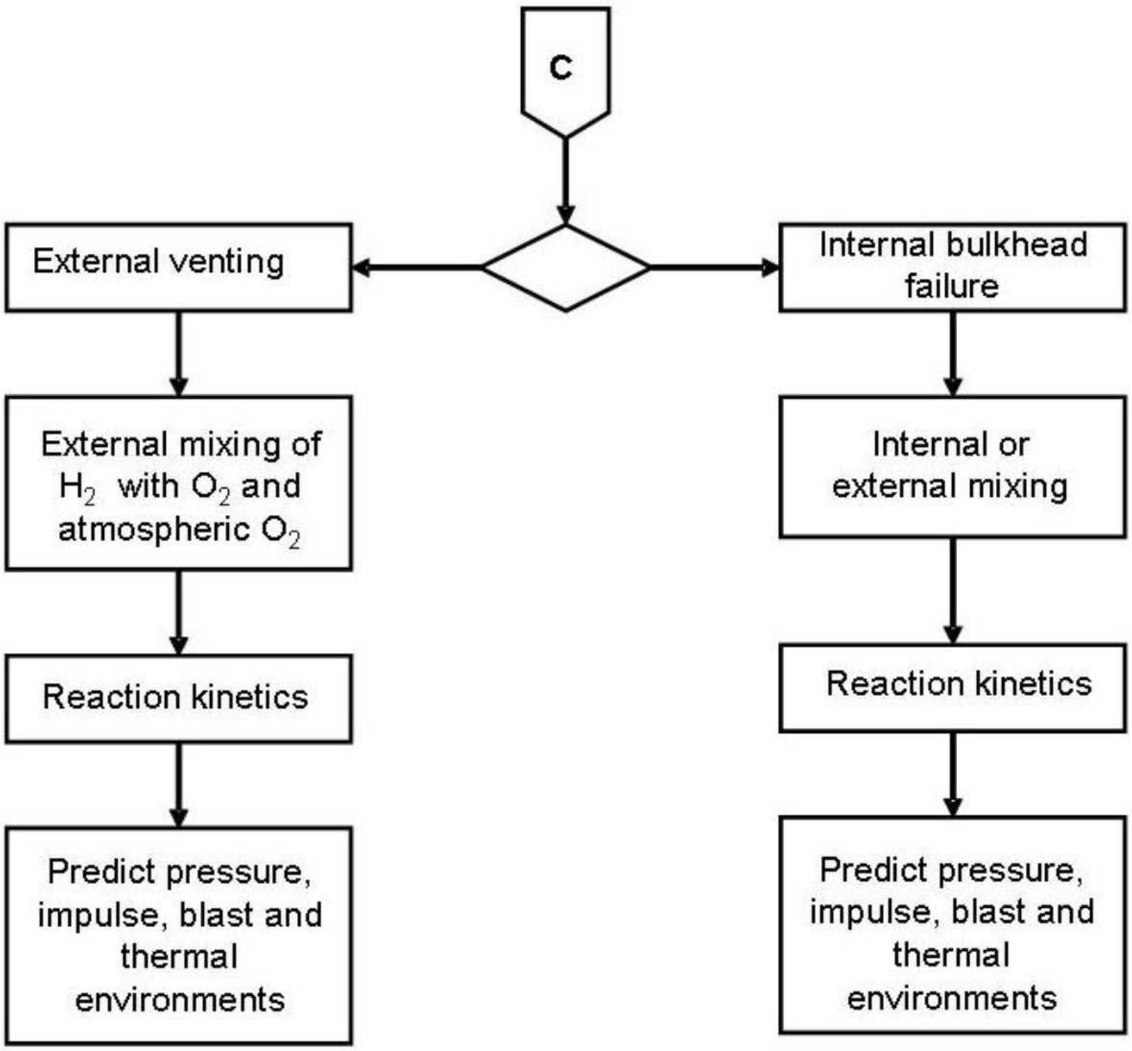

Figure 7.7-4. Analysis Path for Structural Failure

8.0 Findings, Observations, and Recommendations

8.1 Findings

There are no findings in this assessment.

8.2 Observations

The methodologies described in this report are based on five scenario pathways. Specifically, the NESC team considered the following:

1. Perforation of the oxygen tank in the fluid region;
2. Perforation of the oxygen tank in the ullage region;
3. Perforation of the hydrogen tank in the fluid region;
4. Perforation of the hydrogen tank in the ullage region; and
5. Tank failure resulting from the structural response to blast loading.

Collectively, the scenarios include external and internal contact between the LH2 and LO2 propellants and between LH2 and atmospheric oxygen.

O-1 The design of methodologies for the analysis of accidents involving release of propellants from the ARES-1 crew launch vehicle requires a detailed knowledge of accident scenarios including tank rupture, venting, mixing, and reaction behavior.

O-2 In the absence of detailed knowledge of accident scenarios, hypothetical, generic, accident scenarios must be specified to guide the development of methodologies for the assessment of accident environments and effects on the CLV.

O-3 The assessment of the environment produced by tank rupture depends on the time evolution of venting, mixing, and chemical reactions of the propellants. Ultimately, it must be determined if an explosive or combustible environment can occur and, if so, the anticipated characteristics of the resulting energy release. Numerical simulations can provide guidance to assess the physical processes involved in accident scenarios.

O-4 Existing experimental data for LO2 and LH2 interactions should be consulted to guide the development of predictive methodologies for accident analyses. Once specific analyses techniques have been identified, existing experimental data should be used for validation.

8.3 Recommendations

In order to establish a quantitative prediction of physical environments and subsequent vehicle interactions associated with a potential blast environment resulting from an inadvertent release of liquid fuel and oxidant from the US of the ARES-1 CLV during ascent, the following are recommended:

a. Define a suite of credible accident scenarios which affect the US and specify the initial conditions to be imposed on the US.
b. Prior to the analysis of specific scenarios, validate the simulation strategy to the extent possible against available experiments that address the mixing and subsequent reactions involving LO2 and LH2.
c. Conduct the accident analysis for each defined scenario, following the appropriate path of analysis as depicted in figure 7-7.1 through 7-7.4.

9.0 Alternate Viewpoints

There were no alternate viewpoints expressed during this assessment.

10.0 Other Deliverables

There were no other deliverables for this assessment.

11.0 Lessons Learned

There were no lessons learned at this time.

12.0 Definitions of Terms

Combustion A reactive process between a fuel and an oxidant that undergoes a sequence of chemical transformations that produces product gases at high temperature.

Computational Code A set of mathematical and logical steps written in a computer language that translates these rules to electronic instructions in a computer.

Computational Fluid Dynamics A branch of science whereby numerical methods are used to analyze the effects of fluid dynamics.

Deflagration	A subsonic combustion wave that propagates by thermal diffusion effects and generates relatively low pressure rise.
Detonation	A supersonic combustion wave that propagates by shock compression and generates a locally high pressures.
Explosion	A combustion event that causes a sudden release of energy to produce a rapid expansion of high temperature gaseous products and subsequently high pressures and/or shock waves.
Finding	A conclusion based on facts established by the investigating authority.
Impulse	The integral of pressure with respect to time. Impulse is a measure of the change in momentum imparted by a pressure load.
Lessons Learned	Knowledge or understanding gained by experience. The experience may be positive, as in a successful test or mission, or negative, as in a mishap or failure. A lesson must be significant in that it has real or assumed impact on operations; valid in that it is factually and technically correct; and applicable in that it identifies a specific design, process, or decision that reduces or limits the potential for failures and mishaps, or reinforces a positive result.
Methodology	A procedure or set of procedures that includes methods, rules, postulates and analysis principles followed in assessing a problem of inquiry.
Observation	A factor, event, or circumstance identified during the assessment that did not contribute to the problem, but if left uncorrected has the potential to cause a mishap, injury, or increase the severity should a mishap occur. Alternatively, an observation could be a positive acknowledgement of a Center/Program/Project/Organization's operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment/inspection.
Recommendation	An action identified by the assessment team to correct a root cause or deficiency identified during the investigation. The recommendations may be used by the responsible Center/Program/Project/Organization in the preparation of a corrective action plan.

Shock Physics	Shock physics is the field of study involving the physical and chemical behavior of materials when subjected to very rapid and large compressions.
Simulation Software	A computational code that models a real-life or hypothetical situation on a computer.

13.0 Acronyms List

CEV	Crew Exploration Vehicle
CFD	Computational Fluid Dynamics
CLV	Crew Launch Vehicle
CM	Crew Module
HE	High Explosive
JSC	Johnson Space Center
LH2	Liquid Hydrogen
LO2	Liquid Oxygen
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Center
NRB	NESC Review Board
SNL	Sandia National Laboratories
US	Upper Stage
WSTF	White Sands Test Facility

14.0 References

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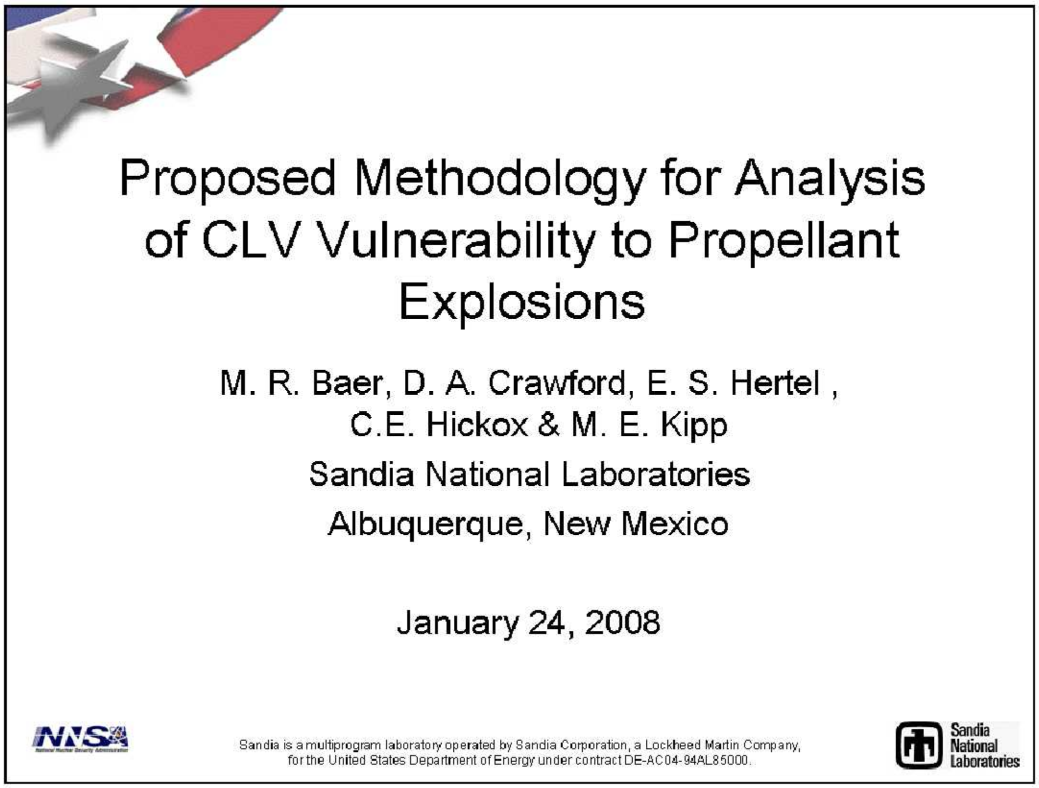
Volume II: Appendix

Appendix A. Proposed Methodology for Analysis of CLV Vulnerability to Propellant Explosions



Purpose and Scope of Work for CLV

- Purpose
  - Understand the potential explosion environment produced by a release of hydrogen from the upper stage
- Scope of Work
  - Recommend methodology for quantitatively characterizing the hydrogen explosion source term
  - Define the path to characterize consequent blast, thermal, and debris environments from CLV on the crew exploration vehicle
- ARES-1 configuration and credible accident scenarios to be provided by NASA

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Overview of Methodology

- Expected sequence of tasks to determine the consequences of hydrogen release (internal and/or external to stage structure)

Define accident scenarios (NASA)

↓

Initial conditions for blast environment

↓

Pressure / impulse / thermal / debris source terms

↓

Environment at Crew Exploration Vehicle

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Define Accident Scenarios (NASA)

- Define potential credible accidents that could release hydrogen
- Examples
  - Debris from solid rocket booster explosion breaching exterior hydrogen tank wall
  - Debris lost from structures forward of stage breaching exterior hydrogen tank wall
  - Hydrogen leak internal to walls reacting with atmospheric oxygen; energy release potential to cause catastrophic rupture of both hydrogen and oxygen tanks
  - Pressure imbalance between hydrogen and oxygen tanks leading to barrier failure
- Scenario defined by NASA tasked to illustrate analysis path and timeline for assessment
  - Identify relevant aspects of physics to be addressed
  - Identify specific codes and outputs from analysis

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Initial Conditions Leading to a Potential Blast Environment

- Initial conditions derived from details from accident scenarios
  - Location of hydrogen release
  - Availability of oxygen (*e.g.*, ambient atmosphere, liquid from tank)
  - Rate and duration of flow, temperature(s) of fuel and environment (determines mixing conditions and stoichiometry of combustion event)
  - Confinement
  - Trajectory location (determines available fuel volumes, vehicle velocity and ambient environments)

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Pressure / Impulse / Thermal / Debris Source Terms

- Initial conditions provide basis for determining source terms (most likely at selected altitudes)
  - Utilize WSTF experimental data to provide additional basis for combustion / energy release rates
  - Recommend a few additional hydrogen / oxygen experiments more relevant to expected accident conditions – (i.e. breach of single tanks; influence of propellant spill rates; dynamic environment effects)
  - This is primarily a turbulent flow mixing problem, *not* a detonation event
  - Use statistical distribution for turbulent combustion with timescale of partition of energy release supporting blast vs. waste heat (volumetric combustion behavior)
    - Fireball characteristics based on existing correlations to determine thermal environment
    - Pressure / impulse
    - Debris (non-shock event should result in relatively large fragments at low velocities)

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Environment at Crew Vehicle

- Source term will define near- and far-field effects
  - Coupled fluid / structural analyses probably not required and one-way coupling expected to be adequate
    - Separate calculations of the blast and the effects on structures
  - Near field: Blast over-pressure / impulse and heat transfer environment at crew vehicle still attached
    (Need to determine if debris can intersect crew vehicle)
  - Far field: Blast over-pressure / impulse, heat transfer, and debris environment at crew vehicle / parachutes
    (Launch abort timing relative to explosion critical in order to determine environment)

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Codes and Data

- Computational tools
  - Computational fluid dynamics / turbulent flow codes to analyze mixing / reaction of hydrogen with on-board oxygen and/or ambient atmosphere
    - (FLOW3D or FLUENT to assess fluid mixing of propellants and CTH to assess release from high pressure reaction products)
  - Chemical equilibrium code with nonideal gas capability to define equation of state and energy release
    - (CHEETAH to define high pressure product EOS and thermochemistry)
  - Shock physics analysis codes to determine blast environment (overpressure and impulse histories) and thermal field of fireball
    - (CTH to determine the shock consequences of the blast field; debris formation and impact dynamics)
  - Structural and aerodynamics codes to address response to blast environment
    - (PRESTO structural mechanics analysis; CALORE thermal analysis; PREMO aerodynamics analysis)
  - Will have to determine fidelity of simulations required (*i.e.*, level of detail in the models and physics required to have confidence that all the significant factors / geometry have been included)
  - Benchmark models / analyses to examples of past accidents

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Experimental & Consultation

- **Experimental data**
  - Reanalyze some of the WSTF LH_2 / LO_2 data in relation to this environment (*i.e.*, volume explosion vs. detonation)
  - Additional experiments may prove vital to understanding this blast environment
    - breakup of propellant tanks
    - better characterization of mixing conditions
- Consultation
  - (*i.e.* Prof. J. E. Shepherd, Caltech, explosion / blast expert)
    - Laboratory experiments and volumetric explosion expertise

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Summary of Methodology

Sequence of tasks to determine consequences of hydrogen release (internal and/or external to the stage structure)

- Define / assess potential credible accidents that would cause release of hydrogen and subsequent explosion
- Evaluate / interpret existing experimental data
- Determine initial conditions of fuel release and / or mixing derived from details of accident scenarios
- Determine energy release / blast effects for scenario of interest
- Blast environment defines near- and far-field pressure / impulse / debris effects
- Wide spectrum of computational tools brought to bear on analysis
- Assessment of the potential accident consequence on the crew exploration vehicle

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14. ABSTRACT
An assessment methodology is developed to guide quantitative predictions of adverse physical environments and the subsequent effects on the Ares-1 crew launch vehicle associated with the loss of containment of cryogenic liquid propellants from the upper stage during ascent. Development of the methodology is led by a team at Sandia National Laboratories (SNL) with guidance and support from a number of National Aeronautics and Space Administration (NASA) personnel. The methodology is based on the current Ares-1 design and feasible accident scenarios. These scenarios address containment failure from debris impact or structural response to pressure or blast loading from an external source. Once containment is breached, the envisioned assessment methodology includes predictions for the sequence of physical processes stemming from cryogenic tank failure. The investigative techniques, analysis paths, and numerical simulations that comprise the proposed methodology are summarized and appropriate simulation software is identified in this report.

15. SUBJECT TERMS
Ares; Crew Launch Vehicle; Crew Module; Feasible accident scenario; Launch Abort System

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